27. The device of Claim 26 wherein the liquid is a dielectric liquid.--

REMARKS

The specification has been amended to update references to the various patent applications referred to therein to cite the now issued patents corresponding thereto. In addition, the reference to the patent application cited on Page 16, line 25, which was filed on the same date as the referenced application, was updated to include the serial number of the application. Contrary to the assertion of the Examiner, the inclusion of the serial number is not new matter because such serial number can be traced from the attorney docket number originally contained on Page 16, line 25 of the application.

The drawings have been objected to under 37 C.F.R. §1.83(a) for failure to show an electromagnetic actuator or an electrostatic actuator. The Examiner is respectfully directed to microactuator 13 shown generally in FIG. 2 and more specifically in FIG. 3. The application, beginning on Page 5, line 7, states that microactuator 13 is preferably an electromagnetic microactuator and more preferably an electrostatic microactuator. Microactuator 13 shown in FIG. 3 is an electrostatic microactuator, which is included in the set of electromagnetic microactuators. It can thus be seen that both an electromagnetic actuator and an electrostatic actuator are shown in the drawings.

Claims 6-12 have been rejected under 35 U.S.C. §101 because it is stated that the disclosed invention inoperative and therefore lacks utility. The Examiner notes that the disclosed device will not operate as an electromagnetic device. As Applicants have stated above, an electrostatic actuator, which is shown in the drawing and described in the application, is included in the set of electromagnetic actuators. Hence, Claims 6-12 are not inoperative and do not lack utility.

Claims 6-12 have been rejected under 35 U.S.C. §112, first paragraph, as containing subject matter which was not described in the specification in such a way as to reasonably convey to one skilled in the relevant art that the inventors, at the time the application was filed, had possession of the claimed invention. In this regard, the Action states: "The specification does not contain an enabling or a full, clear, concise, and exact description of an electromagnetic device. The specification only provides a description of an electrostatic actuator, which is not a magnetic device." Contrary to the assertions of the Examiner, electrostatics is a subset of electromagnetism. As support for this statement, attached hereto are several pages from a book entitled *The Feynman Lectures on Physics, Mainly Electromagnetism and Matter.* Section 1-1 entitled "Electrical Forces" of Chapter 1 entitled "Electromagnetism" states on Page 1-2 commencing at line 36:

We begin by treating only the laws of electricity – including magnetism, which is really a part of the same subject. We have said that the electrical force, like a gravitational force, decreases inversely as the square of the distance between charges. This relationship is called Coulomb's law. But it is not precisely true when charges are moving – the electrical forces depend also on the motions of the charges in a complicated way. One part of the force between moving charges we call the magnetic force. It is really one aspect of an electrical effect. That is why we call the subject "electromagnetism."

As we can see from the foregoing, electrostatics is indeed included in electromagnetism. Hence, a full, clear, concise and exact description of an electromagnetic device has been described in the specification. Accordingly, it is assumed that the rejection under 35 U.S.C. §112, second paragraph, will be withdrawn.

Claims 1-4, 6, 7, 13, 16 and 19 have been rejected under 35 U.S.C. §102(b) as being anticipated by Matsumoto (U.S. Patent No. 5,477,097). Claims 1-3, 6, 7, 8, 11-13, 16, 17 and 19 have been similarly rejected as be anticipated by Cho et al. ("Viscous Energy Dissipation in Laterally Oscillating Planar Microstructures: a Theoretical and Experimental Study"). Claim 5 has been rejected as being unpatentable over Matsumoto. Claims 8-12, 17 and 18 have been similarly rejected as being unpatentable over Matsumoto and Jerman et al. (U.S. Patent No. 5,998,906), Claims 14 and 15 over Matsumoto, Claims 4 and 10 over Cho et al. and Matsumoto, Claim 5 over Cho et al., Claims 9 and 18 over Cho et al. and Jerman et al. and Claims 14 and 15 over Cho et al. Reconsideration of these claims is respectfully requested.

Matsumoto discloses an electrostatic micro-actuator in which a high viscosity fluid having a high dielectric constant is sealed between two electroded fixed members, the high-viscosity fluid surrounding a movable element and the movable element is shaped so as to be stable in the fluid so that even when the speed of the movable element is not high, the movable element can be stably held.. Col. 2, lines 19-25. In FIG. 1, each of the fixed members 7 comprises a plurality of fixed electrodes 1 and an electrical insulating layer 2. Each fixed electrode 1 is fixedly disposed on one of the surfaces of the electrically insulating layer 2. The two fixed members 7 are disposed in parallel with each other with a predetermined gap between them in such a manner that their fixed electrodes 1 oppose one another, and a movable element 6 is provided between these mutually opposing fixed electrodes 1. The movable element 6 has a plurality of movable element electrodes 4 embedded in the electrically insulating layer 3. A high viscosity fluid 5 having an insulating property such as a silicone oil or a fluorine oil is sealed into the gap between the opposed fixed electrodes 1 in which the movable element 6 is provided. The movable element 6 has a stepped shape or a tapered shape so that a positive fluid-pressure distribution is established between the fixed electrodes 1 and the movable element 6. In this way, a dynamic fluid-pressure levitation effect can be expected. Col. 2, lines 43-63. When the movable element 6 approaches one of the upper and lower fixed electrodes 1, a force tending to

push back the movable element 6 to its equilibrium position acts on the movable element 6. Col. 3, lines 7-10. FIG. 3 is a phase/plane diagram which is intended to probe the qualitative phenomenon of motion of the movable element 6 by a stability theory. As the condition of analysis in this diagram, the size of the movable element 6 is 30 mm by 40 mm, the mean gap size is 70.μm, the viscosity of the fluid 5 is 0.8 Pas and the speed of the movable element 6 is 1 mm/sec. Col. 3, .lines 22-28. In FIG. 4, the movable element 6 has a sheet-like stepped shape so that it can move in the rightward direction 9, but a taper shape or a corrugation shape can also be adopted so long as it is stable in fluid. Furthermore, the movable element 6 can have a laterally symmetrical shape so as to move reciprocatingly not in a specific direction. Col. 3, lines 44-50. In FIG. 5, a large number of electrode bearing or supporting members 6 as a sub-system are juxtaposed in such a manner as to move in mutually opposite directions, and the members 6 in the same direction come into contact with respective right and left housing members 11. The housing members 11 are connected to spring components 10. Col. 3, lines 53-58. In this electrostatic micro-actuator, the muscular structure is under the muscle expansion state during the operation of the actuator, and the energy is stored in the spring components 10. When the actuator operation stops, the energy stored in the spring components 10 is released, each electrode support member 6 returns to its initial state, and the muscle contraction state is set up. Col. 3, line 64 to Col. 4, line 3.

Cho et al. disclose in Fig. 1a, b and c a laterally driven planar microdynamic system. The planar microdynamic system is considered as a lumped parameter model, composed of three fundamental components: a planar mass (or inertia), M, for storing kinetic energy; a spring (or flexure suspension), K, for restoring potential energy in its structure; a damper (or dashpot), C, for dissipating energy. The dynamics of the microsystem involves the alternative transfer of energy between its potential and kinetic forms, while dissipating part of the energy during the energy transduction process. Cho et al. further states that in the planar microdevices, the fundamental mechanism of viscous damping is a momentum transport process in a fluid layer. The laterally oscillating planar mass (Fig.1b) is considered as an infinite plate, immersed in an incompressible viscous fluid (either a gas or a liquid) with constant transport properties.

Claim 1, as amended, is patentable by calling for a damped micromechanical device for use with a laser beam comprising a housing provided with an internal fluid-tight chamber, an electrically-driven microactuator disposed in the fluid-tight chamber and having a movable structure capable of being moved between first and second positions at a resonant frequency, a damping fluid disposed in the fluid-tight chamber for damping the movement of the movable structure at the resonant frequency and an optical element carried by the movable structure and disposed in the damping fluid for receiving the laser beam.

Neither Matsumoto nor Cho et al. suggest or disclose a micromechanical device of the type set forth in Claim 1 having, among other things, an optical element carried by the movable structure and disposed in the damping fluid for receiving the laser beam.

Claims 2-15 depend from Claim 1 and are patentable for the same reasons as Claim 1 and by reason of the additional limitations called for therein. Claim 2, for example, is additionally patentable by providing that the damping fluid has a viscosity greater than the viscosity of air for reducing inertial forces on the movable structure due to the buoyancy of the movable structure in the damping fluid.

Amended Claim 16 is a patentable by calling for a damped micromechanical device comprising a housing provided with an internal fluid-tight chamber, an electrostatic microactuator disposed in the fluid-tight chamber, the electrostatic microactuator having a first comb drive member with first comb drive fingers mounted on a substrate and a second comb drive member with second comb drive fingers overlying the substrate and carried by the substrate, the second comb drive member capable of being moved at a resonant frequency between a first stationary position in which the second comb drive fingers are not substantially interdigitated with the first comb drive fingers and a second stationary position in which the second comb drive fingers are substantially interdigitated with the first comb drive fingers and a dielectric liquid disposed in the fluid-tight chamber for damping the movement of the second comb drive member at the resonant frequency and enhancing the electrostatic force between the second comb drive fingers and the first comb drive fingers.

As acknowledged by the Examiner, Matsumoto does not disclose a comb actuator. In addition, neither Matsumoto nor Cho et al. disclose a damped micromechanical device having an electrostatic microactuator in which the second comb drive member is capable of being moved between a first **stationary** (emphasis added) position in which the second comb drive fingers are not substantially interdigitated with the first comb drive fingers and a second **stationary** (emphasis added) position in which the second comb drive fingers are substantially interdigitated with the first comb drive fingers, In this regard, for example, Matsumoto discloses that according to the invention therein, the dynamic stability of the movable element in the electrostatic micro-actuator is substantially equivalent to the stability of the head of the hard disk drive, by keeping the Reynolds number of the system within a stable range. The foregoing cited references also do not disclose such an electrostatic microactuator in which the second comb drive member is capable of being so moved at a resonant frequency.

Nor do Matsumoto or Cho et al. disclose a damped electrostatic microactuator in which a dielectric liquid is disposed in the fluid-tight chamber for damping the movement of the second comb drive member at the resonant frequency. A dielectric liquid is not disclosed in Cho et al.,

and mentioned only in passing in Matsumoto. As noted in the application beginning on Page 12, line 29:

> The damping fluid is preferably a dielectric fluid, that is a substantially insulating fluid, and is typically a dielectric liquid. Since the force produced by an electrostatic actuator is proportional to the magnitude of the dielectric constant of any fluid filling the gap between the electrodes of the actuator, in this instance the gap between stationary comb drive fingers 67 and movable comb drive fingers 72, an increase in force of the microactuator can be provided by increasing the dielectric constant of the damping fluid. The relative dielectric constant of many dielectric fluids is many times greater than the dielectric constant of air, thus providing the same increase in force from a similar microactuator immersed in air for a given voltage and electrode geometry. The dielectric constant of the damping fluid is preferably greater than two and more preferably ranges from three to ten.

The importance of the damping movement at the resonant frequency is noted on Page 12 of the application beginning at line 12.

Claims 17-20 depend from Claim 16 and are patentable for the same reasons as Claim 16 and by reason of the additional limitations called for therein. For example, Claim 17 is additionally patentable by providing that the first and second comb drive members each have a length ranging from 200 to 2000 microns. Although Matsumoto is entitled an electrostatic micro-actuator, the devices disclosed therein are not of micron dimensions. As noted above, for example, Matsumoto discloses in Col. 3, at line 25 that the size of the movable element 6 is 30 mm by 40 mm, the mean gap is 70 μm. As can be appreciated by those skilled in the art, the field of microactuator design is still nascent. Contrary to the belief of the Examiner, it cannot be assumed that any particular actuator configuration can be developed or is physically possible. Hence, there is no reasonable expectation that a relatively large device like that disclosed in Matsumoto can be scaled down to a microactuator of the size called for in Claim 17 and have a fluid therein for damping movement at a resonant frequency. New Claim 20 is additionally patentable by calling for a controller coupled to the first and second comb drive members for closed loop control of the microactuator. Cho et al. does not disclose the novel combination of amended Claim 17.

New Claims 21-27 are different in scope than the claims of record. New Claim 21 is patentable by calling for a damped micromechanical device comprising a housing provided with an internal fluid-tight chamber, a comb assembly disposed in the fluid-tight chamber and having a first comb member mounted on a substrate and a second comb member overlying the substrate and carried by the substrate, the second comb member being movable between first and second

positions relative to the first comb member and a fluid denser than air disposed in the fluid-tight chamber for damping the movement of the second comb member, the housing having a sealable fill hole for introducing the fluid into the fluid-tight chamber. The combination of Claim 21 is not disclosed by the cited references.

Claims 22-27 depend from Claim 21 and are patentable for the same reasons as Claim 21 and by reason of the additional limitations called for therein.

Attached hereto is a marked-up version of the changes made to the claims by the current amendment. The attached page is captioned "Version with Markings to Show Changes Made."

In view of the foregoing, it is respectfully submitted that the claims of record are allowable and that the application should be passed to issue. Should the Examiner believe that the application is not in a condition for allowance and that a telephone interview would help further prosecution of this case, the Examiner is requested to contact the undersigned attorney at the phone number below.

Respectfully submitted,

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By

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VERSION WITH MARKINGS TO SHOW CHANGES MADE

In the specification:

Amend the paragraph beginning on Page 5, line 7 of the application as indicated:

The electrically-driven microactuator 13 can be of any suitable type and is preferably an electromagnetic microactuator in which the movable portion of the microactuator is driven by electromagnetic forces. More preferably, the microactuator 13 is an electrostatic microactuator in which the movable portion of the microactuator is driven by electrostatic forces. Such electrostatic microactuator 13, in general, has similarities to the microactuators disclosed in U.S. ~~patent application Serial No. 09/464,361 filed December 15 , 1999 (Our file No. A-68185), U.S. patent application Serial No. 09/547,698 filed April 12, 2000 (Our file No. A-68187), U.S. patent application Serial No. 09/727,794 filed November 29, 2000 (Our file No. A-70055) and U.S. patent application Serial No. 09/755,743 filed January 5, 2001 (Our file No. A-70217)~~Patent Nos. 6,329,737, 6,384,510, 6,469,415 and 6,333,584, the entire content of each of which is incorporated herein by this reference. In this regard, microactuator 13 is formed on a planar substrate 41 and has a movable structure 42, which includes a mirror holder 43, that overlies substrate 41 (see FIGS. 3 and 4). At least one and as shown a plurality of first and second comb drive assemblies 46 and 47 are carried by substrate 41 for preferably rotating movable structure 42 in first and second opposite directions about an axis of rotation 48 extending perpendicular to planar substrate 41. The axis of rotation is shown as a point in FIG. 3 and labeled by reference line 48. Each of the first and second comb drive assemblies 46 and 47 includes a first drive member or comb drive member 51 mounted on substrate 41 and a second drive member or comb drive member 52 overlying the substrate. The movable structure 42 of rotary microactuator 13 includes second comb drives 52 and is supported or suspended above substrate 41 by first and second spaced-apart springs 43 and 44.

Amend the paragraph beginning on Page 9, line 31 of the application as indicated:

Each of stationary and movable comb drive fingers 67 and 72 is optionally inclined relative to respective bars 66 and 71. That, is each such comb finger is joined to its respective bar at an oblique angle, as disclosed in U.S. ~~patent application Serial No. 09/755,743 filed January 5, 2001~~Patent No. 6,333,584, as opposed to a right angle. The

inclination angle at which each comb drive finger 67 and 72 is joined to its respective bar 66 and 71, measured from a line extending normal to the bar, can range from zero to five degrees and is preferably approximately three degrees. Each movable comb drive finger 72 is further optionally offset relative to the midpoint between the adjacent pair of stationary comb drive fingers 67 between which such movable comb drive finger interdigitates when the second comb drive 52 is electrostatically attracted to the first comb drive 51, also as disclosed in U.S. ~~patent application Serial No. 09/755,743 filed January 5, 2001~~Patent No. 6,333,584. When each movable comb drive finger 72 moves to its second position between the adjacent pair of stationary comb drive fingers 67, the movable comb drive finger becomes centered relative to the midpoint between the adjacent pair of stationary comb drive fingers 67. The offset and inclination of stationary and movable comb drive fingers 67 and 72 serves to accommodate the slight radially-inward shift of the movable comb drive 52 , resulting from the deflection and foreshortening of first and second springs 53 and 54, when movable structure 42 moves from its first position in which springs 53 and 54 are in a straightened position, as shown in FIG. 3, to its second position in which springs 53 and 54 are bent or deflected.

Amend the paragraph beginning on Page 11, line 15 of the application as indicated:

The optical microswitch of package 9 is similar to the optical microswitch disclosed in U.S. ~~patent application Serial No. 09/464,361 filed December 15 , 1999~~Patent No. 6,329,737. In this regard, a micromachined mirror 96 is coupled to microactuator 13 and extends out of the plane of the microactuator. More specifically, micromirror 96 is secured to microactuator 13 by a post preferably formed integral with the mirror 96 and micromachined separately from microactuator 13. The post is joined at its base to mirror holder 43 by any suitable means such as an adhesive. Micromirror 96 has a reflective face or surface 97 and is rotatable by microactuator 13 about axis of rotation 48.

Amend the paragraph beginning on Page 14, line 10 of the application as indicated:

Once package 9 is plugged into place or otherwise mounted into a suitable optical system, for example adjacent the ends of one or more optical fibers in a telecommunication system, and electrically coupled by means of pins 36 to a suitable controller and voltage generator 86, the package 9 can be used for switching laser light

between the one or more optical fibers in the manner disclosed in U.S. ~~patent application Serial No.09/464,373 filed December 15, 1999 (Our file No. A-68184)~~Patent No. 6,301,403, the entire content of which is incorporated herein by this reference. As part of this operation, mirror holder 43 can be rotated in opposite first and second directions of travel about axis of rotation 48 by controller 86. Suitable voltage potentials to first and second drive electrodes 88 and 89 can range from 20 to 250 volts and preferably range from 60 to 180 volts. Microactuator 13 is capable of +/- six degrees of angular rotation, that is a rotation of six degrees in both the clockwise and counterclockwise directions for an aggregate rotation of twelve degrees, when such drive voltages are utilized. Mirror holder 43, and thus micromirror 96, can be stopped and held at any location in such range of motion.

Amend the paragraph beginning on Page 16, line 15 of the application as indicated:

Although the fluid-damped microactuator of the present invention has been shown as being part of ~~a~~an optical microswitch, it should be appreciated that a fluid-damped microactuator can be provided in a variety of other optical components. Further, a fluid-damped microactuator of the present invention can be utilized in other than telecommunications systems. For example, such microactuators can be utilized in data storage systems, for example magneto optical data storage systems. It should also be appreciated that the drag-inducing members of the present invention can be used in undamped microactuators, for example microactuators or other microdevices operated in air. The damping techniques disclosed herein can be used in combination with the damping techniques disclosed in U.S. patent application Serial No. ~~__________~~09/876,265 filed ~~contemporaneously herewith (Our file No. A-70529)~~June 6, 2001, the entire content of which is incorporated herein by this reference. In addition, the damping fluids hereof can also be used with devices other than actuators.

In the claims:

Amend the following claims as indicated:

1. (Amended) A damped micromechanical device for use with a laser beam comprising a housing provided with an internal fluid-tight chamber, an electrically-driven microactuator disposed in the fluid-tight chamber and having a movable structure capable of being moved between first and second positions at a resonant frequency~~and~~, a damping fluid disposed in the

fluid-tight chamber for damping the movement of the movable structure at the resonant frequency and an optical element carried by the movable structure and disposed in the damping fluid for receiving the laser beam.

2. (Amended) The device of Claim 1 wherein the damping fluid has a viscosity greater than the viscosity of air for reducing inertial forces on the movable structure due to the buoyancy of the movable structure in the damping fluid.

16. (Amended) A damped micromechanical device comprising a housing provided with an internal fluid-tight chamber, an electrostatic microactuator disposed in the fluid-tight chamber ~~and having a stationary structure and a movable structure~~, the electrostatic microactuator having a first comb drive member with first comb drive fingers mounted on a substrate and a second comb drive member with second comb drive fingers overlying the substrate and carried by the substrate, the second comb drive member capable of being moved ~~between first and second positions~~ at a resonant frequency ~~relative to the stationary structure~~between a first stationary position in which the second comb drive fingers are not substantially interdigitated with the first comb drive fingers and a second stationary position in which the second comb drive fingers are substantially interdigitated with the first comb drive fingers and a dielectric liquid disposed in the fluid-tight chamber for damping the movement of the ~~movable structure~~second comb drive member at the resonant frequency and enhancing the electrostatic force between the ~~stationary structure~~second comb drive fingers and the ~~movable structure~~first comb drive fingers.

17. (Amended) The device of Claim 16 wherein the microactuator includes ~~a substrate, at least one comb drive assembly having a first comb drive member mounted on the substrate and a second comb drive member overlying the substrate,~~ at least one spring member having a first end portion coupled to the substrate and a second end portion coupled to the ~~movable structure, the movable structure including the~~ second comb drive member~~and the second comb drive member being movable at the resonant frequency between first and second positions relative to the first comb drive member~~.

18. (Amended) The device of Claim ~~17~~16 wherein the first and second comb drive ~~member has a plurality of first comb drive fingers and the second comb drive member has a plurality of second comb drive fingers, the second comb drive fingers being not substantially fully interdigitated with the first comb drive fingers when the second comb drive member is in the first position and the second comb drive fingers being substantially fully interdigitated with~~

~~the first comb drive fingers when the second comb drive member is in the second position~~ members each have a length ranging from 200 to 2000 microns.

Add the following claims:

20. The device of Claim 16 further comprising a controller coupled to the first and second comb drive members for closed loop control of the microactuator.

21. A damped micromechanical device comprising a housing provided with an internal fluid-tight chamber, a comb assembly disposed in the fluid-tight chamber and having a first comb member mounted on a substrate and a second comb member overlying the substrate and carried by the substrate, the second comb member being movable between first and second positions relative to the first comb member and a fluid denser than air disposed in the fluid-tight chamber for damping the movement of the second comb member, the housing having a sealable fill hole for introducing the fluid into the fluid-tight chamber.

22. The device of Claim 21 wherein the comb assembly is a comb drive assembly of a microactuator disposed in the fluid-tight chamber.

23. The device of Claim 21 wherein the housing is made of ceramic.

24. The device of Claim 21 for use with a laser beam further comprising an optical element carried by the second comb member within the fluid-tight chamber for receiving the laser beam.

25. The device of Claim 21 for use with a laser beam wherein the housing is provided with a window for permitting passage of the laser beam into the fluid-tight chamber.

26. The device of Claim 21 wherein the fluid is a liquid.

27. The device of Claim 26 wherein the liquid is a dielectric liquid.

The Feynman LECTURES ON PHYSICS

MAINLY ELECTROMAGNETISM AND MATTER

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1

Electromagnetism

Review: Chapter 12, Vol. I, *Characteristics of Force*

1–1 Electrical forces

Consider a force like gravitation which varies predominantly inversely as the square of the distance, but which is about a *billion-billion-billion-billion* times stronger. And with another difference. There are two kinds of "matter," which we can call positive and negative. Like kinds repel and unlike kinds attract—unlike gravity where there is only attraction. What would happen?

A bunch of positives would repel with an enormous force and spread out in all directions. A bunch of negatives would do the same. But an evenly mixed bunch of positives and negatives would do something completely different. The opposite pieces would be pulled together by the enormous attractions. The net result would be that the terrific forces would balance themselves out almost perfectly, by forming tight, fine mixtures of the positive and the negative, and between two separate bunches of such mixtures there would be practically no attraction or repulsion at all.

There is such a force: the electrical force. And all matter is a mixture of positive protons and negative electrons which are attracting and repelling with this great force. So perfect is the balance, however, that when you stand near someone else you don't feel any force at all. If there were even a little bit of unbalance you would know it. If you were standing at arm's length from someone and each of you had *one percent* more electrons than protons, the repelling force would be incredible. How great? Enough to lift the Empire State Building? No! To lift Mount Everest? No! The repulsion would be enough to lift a "weight" equal to that of the entire earth!

With such enormous forces so perfectly balanced in this intimate mixture, it is not hard to understand that matter, trying to keep its positive and negative charges in the finest balance, can have a great stiffness and strength. The Empire State Building, for example, swings only eight feet in the wind because the electrical forces hold every electron and proton more or less in its proper place. On the other hand, if we look at matter on a scale small enough that we see only a few atoms, any small piece will not, usually, have an equal number of positive and negative charges, and so there will be strong residual electrical forces. Even when there are equal numbers of both charges in two neighboring small pieces, there may still be large net electrical forces because the forces between individual charges vary inversely as the square of the distance. A net force can arise if a negative charge of one piece is closer to the positive than to the negative charges of the other piece. The attractive forces can then be larger than the repulsive ones and there can be a net attraction between two small pieces with no excess charges. The force that holds the atoms together, and the chemical forces that hold molecules together, are really electrical forces acting in regions where the balance of charge is not perfect, or where the distances are very small.

You know, of course, that atoms are made with positive protons in the nucleus and with electrons outside. You may ask: "If this electrical force is so terrific, why don't the protons and electrons just get on top of each other? If they want to be in an intimate mixture, why isn't it still more intimate?" The answer has to do with the quantum effects. If we try to confine our electrons in a region that is very close to the protons, then according to the uncertainty principle they must have some mean square momentum which is larger the more we try to confine them. It is this motion, required by the laws of quantum mechanics, that keeps the electrical attraction from bringing the charges any closer together.

There is another question: "What holds the nucleus together"? In a nucleus there are several protons, all of which are positive. Why don't they push themselves apart? It turns out that in nuclei there are, in addition to electrical forces, nonelectrical forces, called nuclear forces, which are greater than the electrical forces and which are able to hold the protons together in spite of the electrical repulsion. The nuclear forces, however, have a short range—their force falls off much more rapidly than $1/r^2$. And this has an important consequence. If a nucleus has too many protons in it, it gets too big, and it will not stay together. An example is uranium, with 92 protons. The nuclear forces act mainly between each proton (or neutron) and its nearest neighbor, while the electrical forces act over larger distances, giving a repulsion between each proton and all of the others in the nucleus. The more protons in a nucleus, the stronger is the electrical repulsion, until, as in the case of uranium, the balance is so delicate that the nucleus is almost ready to fly apart from the repulsive electrical force. If such a nucleus is just "tapped" lightly (as can be done by sending in a slow neutron), it breaks into two pieces, each with positive charge, and these pieces fly apart by electrical repulsion. The energy which is liberated is the energy of the atomic bomb. This energy is usually called "nuclear" energy, but it is really "electrical" energy released when electrical forces have overcome the attractive nuclear forces.

We may ask, finally, what holds a negatively charged electron together (since it has no nuclear forces). If an electron is all made of one kind of substance, each part should repel the other parts. Why, then, doesn't it fly apart? But does the electron have "parts"? Perhaps we should say that the electron is just a point and that electrical forces only act between *different* point charges, so that the electron does not act upon itself. Perhaps. All we can say is that the question of what holds the electron together has produced many difficulties in the attempts to form a complete theory of electromagnetism. The question has never been answered. We will entertain overselves by discussing this subject some more in later chapters.

As we have seen, we should expect that it is a combination of electrical forces and quantum-mechanical effects that will determine the detailed structure of materials in bulk, and, therefore, their properties. Some materials are hard, some are soft. Some are electrical "conductors"—because their electrons are free to move about; others are "insulators"—because their electrons are held tightly to individual atoms. We shall consider later how some of these properties come about, but that is a very complicated subject, so we will begin by looking at the electrical forces only in simple situations. We begin by treating only the laws of electricity—including magnetism, which is really a part of the same subject.

We have said that the electrical force, like a gravitational force, decreases inversely as the square of the distance between charges. This relationship is called Coulomb's law. But it is not precisely true when charges are moving—the electrical forces depend also on the motions of the charges in a complicated way. One part of the force between moving charges we call the *magnetic* force. It is really one aspect of an electrical effect. That is why we call the subject "electromagnetism."

There is an important general principle that makes it possible to treat electromagnetic forces in a relatively simple way. We find, from experiment, that the force that acts on a particular charge—no matter how many other charges there are or how they are moving—depends only on the position of that particular charge, on the velocity of the charge, and on the amount of charge. We can write the force $\boldsymbol{F}$ on a charge q moving with a velocity $\boldsymbol{v}$ as

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{1.1}$$

We call $\boldsymbol{E}$ the *electric field* and $\boldsymbol{B}$ the *magnetic field* at the location of the charge. The important thing is that the electrical forces from all the other charges in the universe can be summarized by giving just these two vectors. Their values will depend on *where* the charge is, and may change with *time*. Furthermore, if we replace that charge with another charge, the force on the new charge will be just in proportion to the amount of charge so long as all the rest of the charges in the

Lower case Greek letters and commonly used capitals

α		alpha
β		beta
γ	Γ	gamma
δ	Δ	delta
ϵ		epsilon
ζ		zeta
η		eta
θ	Θ	theta
ι		iota
κ		kappa
λ	Λ	lambda
μ		mu
ν		nu
ξ	Ξ	xi (ksi)
o		omicron
π	Π	pi
ρ		rho
σ	Σ	sigma
τ		tau
υ	Υ	upsilon
ϕ	Φ	phi
χ		chi (khi)
ψ	Ψ	psi
ω	Ω	omega

world do not change their positions or motions. (In real situations, of course, each charge produces forces on all other charges in the neighborhood and may cause these other charges to move, and so in some cases the fields *can* change if we replace our particular charge by another.)

We know from Vol. I how to find the motion of a particle if we know the force on it. Equation (1.1) can be combined with the equation of motion to give

$$\frac{d}{dt}\left[\frac{m\boldsymbol{v}}{(1 - v^2/c^2)^{1/2}}\right] = \boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}). \tag{1.2}$$

So if $\boldsymbol{E}$ and $\boldsymbol{B}$ are given, we can find the motions. Now we need to know how the $\boldsymbol{E}$'s and $\boldsymbol{B}$'s are produced.

One of the most important simplifying principles about the way the fields are produced is this: Suppose a number of charges moving in some manner would produce a field $\boldsymbol{E}_1$, and another set of charges would produce $\boldsymbol{E}_2$. If both sets of charges are in place at the same time (keeping the same locations and motions they had when considered separately), then the field produced is just the sum

$$\underline{\boldsymbol{E} = \boldsymbol{E}_1 + \boldsymbol{E}_2.} \tag{1.3}$$

This fact is called *the principle of superposition* of fields. It holds also for magnetic fields.

This principle means that if we know the law for the electric and magnetic fields produced by a *single* charge moving in an arbitrary way, then all the laws of electrodynamics are complete. If we want to know the force on charge A we need only calculate the $\boldsymbol{E}$ and $\boldsymbol{B}$ produced by each of the charges B, C, D, etc., and then add the $\boldsymbol{E}$'s and $\boldsymbol{B}$'s from all the charges to find the fields, and from them the forces acting on charge A. If it had only turned out that the field produced by a single charge was simple, this would be the neatest way to describe the laws of electrodynamics. We have already given a description of this law (Chapter 28, Vol. I) and it is, unfortunately, rather complicated.

It turns out that the form in which the laws of electrodynamics are simplest are not what you might expect. It is *not* simplest to give a formula for the force that one charge produces on another. It is true that when charges are standing still the Coulomb force law is simple, but when charges are moving about the relations are complicated by delays in time and by the effects of acceleration, among others. As a result, we do not wish to present electrodynamics only through the force laws between charges; we find it more convenient to consider another point of view—a point of view in which the laws of electrodynamics appear to be the most easily manageable.

1–2 Electric and magnetic fields

First, we must extend, somewhat, our ideas of the electric and magnetic vectors, $\boldsymbol{E}$ and $\boldsymbol{B}$. We have defined them in terms of the forces that are felt by a charge. We wish now to speak of electric and magnetic fields *at a point* even when there is no charge present. We are saying, in effect, that since there are forces "acting on" the charge, there is still "something" there when the charge is removed. If a charge located at the point (x, y, z) at the time t feels the force $\boldsymbol{F}$ given by Eq. (1.1) we associate the vectors $\boldsymbol{E}$ and $\boldsymbol{B}$ with *the point* in space (x, y, z). We may think of $\boldsymbol{E}(x, y, z, t)$ and $\boldsymbol{B}(x, y, z, t)$ as giving the forces that *would be* experienced at the time t by a charge located at (x, y, z), *with the condition* that placing the charge there *did not disturb* the positions or motions of all the other charges responsible for the fields.

Following this idea, we associate with *every* point (x, y, z) in space two vectors $\boldsymbol{E}$ and $\boldsymbol{B}$, which may be changing with time. The electric and magnetic fields are, then, viewed as *vector functions* of x, y, z, and t. Since a vector is specified by its components, each of the fields $\boldsymbol{E}(x, y, z, t)$ and $\boldsymbol{B}(x, y, z, t)$ represent three mathematical functions of x, y, z, and t.